Constraining low scale gravity with ultrahigh energy neutrinos

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We show that LSG model predictions of event ratios are clearly distinguished from those of the SM. This is true in all models of ultrahigh energy (UHE) neutrino sources, in both $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ and $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ scenarios for the flux incident on earth. In particular the ratios of upward μ events to upward shower events and the ratios of up events to down events are different by a factor of 2 to an order of magnitude in the comparisons between SM and LSG. ν_τ rates are low but show high sensitivity to SM vs LSG interaction physics.

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I. INTRODUCTION

There are a number of models predicting the existence of UHE (energies of a PeV and higher) neutrinos. It is very likely that UHE neutrinos exist as UHE cosmic rays have been observed and most of the models that account for these cosmic rays also guarantee the existence of UHE neutrinos.

Let us assume these neutrinos exist and we want to detect them. We know nothing about their interactions at UHE energies and we do not know their fluxes either. In this paper we differentiate, independent of the input neutrino flux model, between two possibilities for UHE neutrino-nucleon interactions. One is an extrapolation to of standard model (SM) weak interaction cross sections to ultrahigh energies and the other is anomalous rise in the cross sections at ultrahigh energies as predicted by low scale gravity (LSG) models [1, 2, 3]. Although we consider a particular low scale gravity scenario with large extra dimensions, our results are applicable to any models which give similar cross sections at UHE energies.

For an analysis that does not depend on the normalization of the input flux, we look at up-to-down ratios of the muon, tau, and shower events for an icecube-like detector[4, 5]. To do that, one needs to know upward and downward neutrino flux at the detector site (south pole for icecube) for a given flux model. For input flux we consider the models SDSS[6], WB[7](WB flux bound), Protheroe[8], Mannheim (B) [9] models.

The Earth is nearly opaque to UHE neutrinos (Earth is almost transparent to neutrinos of energies below a 50TeV or so) and hence we solve integro-differential equations for neutrino propagation through the Earth to calculate the upward neutrino fluxes (neutrino fluxes coming through the earth) at the detectors. In Section II we look at the cross sections involved in neutrino-nucleon interactions, and propagation of the flux through the earth. Section III has results and discussion for event rates, and Section IV gives the summary.

II. NEUTRINO PROPAGATION THROUGH THE EARTH

In LSG models, in addition to the SM neutral current (NC) and charged current (CC) weak interactions, neutrinos interact with nucleons via graviton exchange or they can form micro black holes. Graviton exchange process is calculated in the eikonal (EK) approximation, and for black hole formation (BH) one uses the geometric cross section. Here we are interested in the detectable effects of these processes without going into theoretical details of the processes. The EK process will initiate a particle shower. The BH process also gives a particle shower via Hawking radiation, as the micro black hole, unlike a macro black hole, has extremely short life time due to its tiny mass. Presumably these particle showers will produce radio and optical radiation which can be detected.

For UHE neutrinos, LSG models predict dominance of graviton exchange (EK) and black hole formation (BH) over the extrapolated standard model interactions. However, these models do not set the energy scale at which this happens. Also, the number of extra dimensions is a free parameter. In this paper we look at the interesting case of 1 TeV and 2 TeV scale LSG models as this scale is close to the weak scale and, also as we will see later, UHE neutrinos can be useful to give us signals of LSG only around this scale. Reference[4] has the cross sections and interaction

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TABLE I: Up and down events yr^{-1} (in the flux models SD[6] (or SDSS), WB[7], PR[8], and MB[9]) for detector threshold $E = 0.5PeV$ in the scenario $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$; results are shown for the standard model (SM), and low scale gravity with 6 extra dimensions and mass scales 1TeV (G1) and 2TeV (G2) (for details see Ref.[4]). All upward events are integrated over nadir angle $\theta \leq 84^0$; down showers are integrated over angle but muons and taus are not.

	showers ($\frac{up}{down}$)			muons ($\frac{up}{down}$)			taus ($\frac{up}{down}$)		
	SM	$G2$	$G1$	SM	$G2$	$G1$	SM	$G2$	$G1$
WB	$\frac{2.6}{11}$	$\frac{2.7}{24}$	$\frac{3.1}{201}$	$\frac{3.0}{3.3}$	$\frac{2.7}{3.3}$	$\frac{1.1}{3.3}$	$\frac{0.11}{0.13}$	$\frac{.074}{0.13}$	$\frac{0.0086}{0.13}$
SD	$\frac{163}{622}$	$\frac{167}{748}$	$\frac{202}{4725}$	$\frac{176}{142}$	$\frac{165}{142}$	$\frac{74}{142}$	$\frac{4.7}{4.6}$	$\frac{4.0}{4.6}$	$\frac{0.54}{4.6}$
MB	$\frac{3.0}{30}$	$\frac{3.1}{195}$	$\frac{2.2}{1898}$	$\frac{6.4}{18}$	$\frac{3.6}{18}$	$\frac{0.66}{18}$	$\frac{0.46}{0.86}$	$\frac{0.20}{0.86}$	$\frac{0.01}{0.86}$
PR	$\frac{32}{182}$	$\frac{33}{534}$	$\frac{34}{5284}$	$\frac{50}{73}$	$\frac{38}{73}$	$\frac{12}{73}$	$\frac{2.4}{3.5}$	$\frac{1.5}{3.5}$	$\frac{0.13}{3.5}$

lengths for neutrino-nucleon interactions in SM and LSG. To calculate the upward neutrino flux at the detector we need to propagate not only three neutrino flavors but also the τ's produced in CC interactions of $\nu\tau$'s[4]. These taus will decay and produce more neutrinos of all flavors hence we cannot ignore them. We do not need to propagate electrons, muons, and hadrons produced by neutrinos during their propagation, as excluding them does not have any significant effect on the neutrino flux propagation. The numerical solution of the coupled integro-differential equations of propagation in SM and LSG, for three neutrino flavors and the taus, gives us the final upward neutrino flux at the detector site. This flux will be different in SM and LSG due to different interactions involved in the neutrino propagation. The over all effect of LSG is to give a stronger suppression of the upward flux as compared to the SM case.

III. EVENT RATES

With the propagated flux in hand, we calculate the upward and down shower, muon, and tau event rates[4] due to different neutrino interactions in SM and LSG. An ICECUBE-like detector is capable of detecting muons by their tracks, taus by some tagged tau events as explained below, and showers by the optical radiation they produce.

There are two sources of muon events: (i) muons from $\nu\mu$-nucleon CC interaction (ii) muons from decays of the taus produced in a $\nu\tau$-nucleon CC interaction. As LSG does not introduce any interaction analogous to CC interaction in SM, one expects the muon events will be the same in SM and LSG provided the neutrino flux is the same in the two. This means the down muon events will be the same in SM and LSG but upward muon events will be smaller in LSG as the upward neutrino flux is smaller in LSG as compared to the one in SM.

The only source of taus is $\nu\tau$-nucleon CC interaction. As explained below, tagging taus is harder than tagging muons, as one cannot tag taus by detecting their tracks alone. Fortunately, there are other ways to tag tau events by detecting[4]: (i) a track and a particle shower at the end of the track.(ii) a shower, a track, and then a shower again.(iii) a tau track and the muon track after muonic tau decay. However, it turns out that all the above three event types for tagging taus are only a few in number for any neutrino flux model. For the same reason as mentioned above for muons, the tagged tau down events will be the same in SM and LSG but the upward events will be larger in SM as compared to LSG.

Shower events are detected by the radiation coming from the particle showers. These particle showers are produced in all neutrino-nucleon interactions in SM (NC+CC) and LSG (EK+BH). However, for a given neutrino flux, we expect to see more showers in LSG as compared to SM; This is because for LSG we have, in addition to CC and NC interactions, much bigger EK and BH cross sections.

In table I we show up-to-down event rates for showers, muons, and taus in SM and LSG for different input flux models. Here we see the shower muon rates are significant for all the flux models and both in MS and LSG. One the other hand the tau rates are very small as we anticipated. In table II, to better differentiate between SM and LSG, we show some ratios of the event rate ratios in the flavor scenarios $\nu_e : \nu_\mu : \nu_\tau :: 1 : 2 : 0$ and $\nu_e : \nu_\mu : \nu_\tau :: 1 : 1 : 1$ for the input flux at the Earth. Here we see the ratio of the showers down to muons up is more than an order of magnitude larger in LSG, with 1 TeV mass scale, as compared to SM. This is true in both of the flavor scenarios. For the 2 TeV scale gravity, the difference between SM and LSG are not as large. As we see in table II, the up-to-down tagged tau event ratios will also be very useful in constraining low scale gravity.

TABLE II: Ratios of the ratios (detector threshold $E = 0.5PeV$); here $RR1=\frac{showers\ down}{muons\ up}$ and $RR2=\frac{taus\ down}{taus\ up}$. Results are shown fo two different flavor scenarios.

	$\frac{RR1_{G2}}{RR1_{SM}}$		$\frac{RR1_{G1}}{RR1_{SM}}$		$\frac{RR2_{G2}}{RR2_{SM}}$	$\frac{RR2_{G1}}{RR2_{SM}}$
	1 : 2 : 0	1 : 1 : 1	1 : 2 : 0	1 : 1 : 1		
WB	$\frac{4.5}{1.7}$=2.7	$\frac{8.8}{3.6}$=2.4	$\frac{93}{1.7}$=56	$\frac{183}{3.6}$=50	1.5	13
SD	$\frac{2.1}{1.6}$= 1.3	$\frac{4.5}{3.5}$=1.3	$\frac{34}{1.6}$= 21	$\frac{64}{3.5}$=18	1.2	8.7
MB	$\frac{30}{2.1}$= 14	$\frac{54}{4.7}$=11	$\frac{1571}{2.1}$= 735	$\frac{2875}{4.7}$=610	2.3	46
PR	$\frac{7.4}{1.6}$=4.7	$\frac{14}{3.6}$=3.9	$\frac{249}{1.6}$=157	$\frac{440}{3.6}$=121	1.6	18

IV. SUMMARY

The following comments are true for all the neutrino flux models we have considered (see Ref.[4]): (i) Even at thresholds as large as 0.5PeV, the showers and muon event rates are large enough to give a significant signal in an ICECUBE-like detector. (ii) Although LSG (1-2TeV scale) sets in around 2-20PeV neutrino energies, it is possible (due to neutrino feed down effect) to distinguish between SM and LSG (1-2TeV) even at lower energy thresholds. Even at energy thresholds as low as 0.5PeV the event ratios of showers down to muons up are significantly large in LSG (1-2TeV) as compared to SM. This is true for both flavor scenarios ($\nu_e : \nu_\mu : \nu_\tau :: 1:2:0$ and $\nu_e : \nu_\mu : \nu_\tau :: 1:1:1$). (iii) Tagged tau neutrino events, although very small, are useful in differentiating between SM and LSG (1TeV). The event ratios of taus down to taus up are significantly large in LSG (1TeV) as compared to SM. The taus are not a very useful tool in differentiating between SM and LSG with scale of 2TeV and higher. (iv) To differentiate between SM and LSG with scales higher than 2TeV, one needs to look at events with thresholds higher than 10PeV which makes it very hard as the neutrino fluxes fall very rapidly at higher energies.

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